

Hydrogen-Induced Material Degradation: Brittle Decohesion Versus Plastic Flow Localization

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PIs: Petros Sofronis¹ and Robert O. Ritchie²

¹Department of Theoretical and Applied Mechanics, University of Illinois at Urbana-Champaign

²Department of Materials Science and Engineering, University of California, Berkeley.

A central issue in material safety is the understanding of the hydrogen-induced catastrophic fracture of materials sometimes after many years of service. When hydrogen is present, materials fail at load levels that are very low compared with those that a hydrogen-free material can sustain. The result is usually catastrophic failure which occurs unexpectedly, sometimes after many years of service. In general, the subject is complicated and has become a source of controversy. Despite extensive study over the past 25 years, a complete mechanistic understanding of the hydrogen embrittlement phenomena has yet to be achieved.

Earlier scientists, misled by the absence of substantial macroscopic deformation of material components upon fracture in the presence of hydrogen, surmised that hydrogen would make a material (e.g. aluminides, iron, steels, nickel, and their alloys) become brittle, thus causing it to break easier only by decohesion. However, careful microscopic observations and finite element calculations have demonstrated that hydrogen enhances dislocation mobility and thereby the capability of a material to deform under load thus suppressing decohesion. This counterintuitive argument says that the macroscopic ductility is limited by the onset of extensive localized plasticity. As a result, apart from decohesion, the material degradation mechanism almost always involves highly localized ductile rupture processes.

The prime objective of the project is to discern in a quantitative fashion the fundamental mechanism(s) responsible for the hydrogen-induced degradation of both model and industrially-relevant engineering materials. Experimental observations on hydrogen enhanced dislocation mobility and lattice dilatation are used to describe the macroscopic flow characteristics and constitutive response of materials in the presence of hydrogen. The techniques of solid mechanics are then employed to understand and analyze how the concurrent action

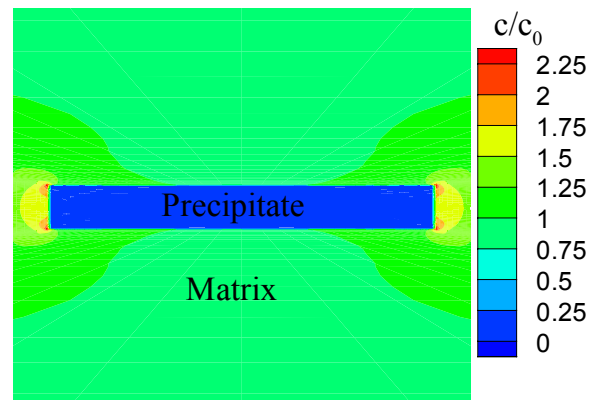


Fig. 1. Contour plot of normalized hydrogen concentration around a precipitate in nickel-base alloy 690. The initial stress-free concentration c_0 is equal to 0.001 hydrogen atoms per metal atom

of hydrogen-induced material softening and decohesion can trigger a fracture event that leads to material failure. Loss of ellipticity in the governing equations for the macroscopic behavior was shown to promote shear band localization in agreement with experimental observations that hydrogen limits macroscopic ductility by promoting the onset of extensive localized plasticity, that is, for "slippery" material response. The Rice and Hirth thermodynamic theory of decohesion is currently being implemented in a boundary value problem setting and its predicting capability is being tested in the case of decohesion along grain boundary carbides in nickel base superalloy 690. Evaluation of the grain boundary weakening by impurities and its concomitant effect on bulk plasticity are necessary in order to assess and extend the application of the theory to cases in which decohesion proceeds under non-equilibrium conditions. Figure 1 shows contour plots of the normalized hydrogen concentration c/c_0 around a carbide. Significant enhancement of hydrogen concentration is seen near the edges of the precipitate. This enhancement is due to the elevation of both hydrostatic stress and plastic strain in the immediate neighborhood of the precipitate induced by the lattice misfit strain. Having calculated the amount of hydrogen attracted by the precipitate, we estimated the trap binding energy of the perfectly bonded precipitate to be of the order of 10KJ/mole. Currently, calculations are being carried out with semi-coherent precipitates. Such a semi-coherent interface can act as a sink for hydrogen atoms thereby enhancing the local hydrogen concentrations to levels greater than those shown in the figure, thus further accelerating the degradation event.